Journal of Volcanology and Geothermal Research 177 (2008) 687–694

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

Satellite observations reveal little inter-annual variability in the radiant flux from the Mount Erebus lava lake

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ARTICLE INFO

Article history:
Received 17 May 2007
Accepted 8 March 2008
Available online 19 March 2008

Keywords:
Erebus
remote sensing
MODIS

ABSTRACT

Satellite remote sensing represents a mature technology for long-term monitoring of volcanic activity at Mount Erebus, either independently or as a complement to field instrumentation. Observations made on 4290 discrete occasions over a six year period by NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) indicate that the radiant flux from the volcano's summit crater (and by inference, the lava lake contained therein), while variable on the time scale of days to weeks, has varied little on an inter-annual basis over this period. The average radiant flux from the lake during this time was 15 MW, with a maximum flux of 100 MW. Such heat flux time-series have been shown to act as a reliable proxy for general levels of activity at erupting volcanoes around the world, particularly when these time-series are of a long duration. The apparent stability of Erebus' power output is in marked contrast to fluxes observed at three other terrestrial volcanoes, Erta 'Ale (Ethiopia), Nyiragongo (Democratic Republic of Congo) and Ambrym (Vanuatu), which, while also hosting active lava lakes, all exhibit much greater variability in radiant flux over the same period of time. The results presented in this paper are confluent with those obtained from geochemical considerations of the Erebus' degassing regime, and confirm that remarkably stable open-system volcanism appears to be characteristic of this long-active volcano.

1. Introduction

Mount Erebus is Earth's southernmost active volcano (Fig. 1). Sighted and named by James Clark Ross in 1841, an active lava lake was first observed in 1972 (Giggenbach et al., 1973), although this may have persisted throughout the intervening period (Rose et al., 1985). At the present time, activity at Erebus is characterised by the continued presence of a phonolitic lava lake, the surface of which is intermittently disrupted by strombolian explosions, and persistent degassing. Although the volcano presents no significant hazard, there are many reasons why it is important to monitor its behaviour. These include the rarity of the composition of its erupted lavas, its status as one of only a handful of terrestrial volcanoes to host a persistently active lava lake and the longevity of its eruptive activity. However, the high latitude of Erebus ensures that continuous monitoring of the volcano is a challenge. Severe cold, wind, and (outside the Austral summer) darkness, mean that although an extensive in situ monitoring network exists, maintaining it in a permanently operational state is difficult (Aster et al., 2004). As such, long-term monitoring using Earth-orbiting satellites constitutes a useful complement to the ground-based monitoring effort, particularly during the long Antarctic winter.

Remotely sensed observations of Mount Erebus have been published before (e.g. Rothery and Oppenheimer, 1994; Harris et al., 1999a), and have been concerned primarily with determining the intensity of the radiant flux from the volcano's summit crater region. This is also the focus of this paper. The significance of the new data we present here stems largely from the duration over which the measurements have been made and their temporal frequency. The Moderate Resolution Imaging Spectroradiometer (MODIS) has, weather permitting, made observations of Mount Erebus every day since 26 February 2000. MODIS measures the spectral radiance reflected and emitted from Earth's surface in 36 wavebands (spanning the wavelength interval 0.40 to 14.4 μm) at spatial resolutions of 250, 500 and 1000 m (see Barnes et al., 1998 for details). Prior to June 2002 only one MODIS sensor was operational (that flown onboard NASA's Terra satellite). Since that time a second MODIS sensor (carried by Terra's sister-ship, Aqua) has also been in orbit acquiring equivalent data, albeit at slightly different times of day. These contrasting orbits and the fact that MODIS images acquired on adjacent orbital tracks overlap significantly at high latitudes, means that Erebus can be observed by MODIS as many as 16 times in any given 24 h period (i.e. the number of times Erebus falls within ±55° of the Terra or Aqua sub-satellite point). This allows not only the compilation of extended satellite time-series of the thermal radiance it emits, but also ameliorates the effect that intermittent cloud cover has on such a record.

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doi:10.1016/j.jvolgeores.2008.03.005

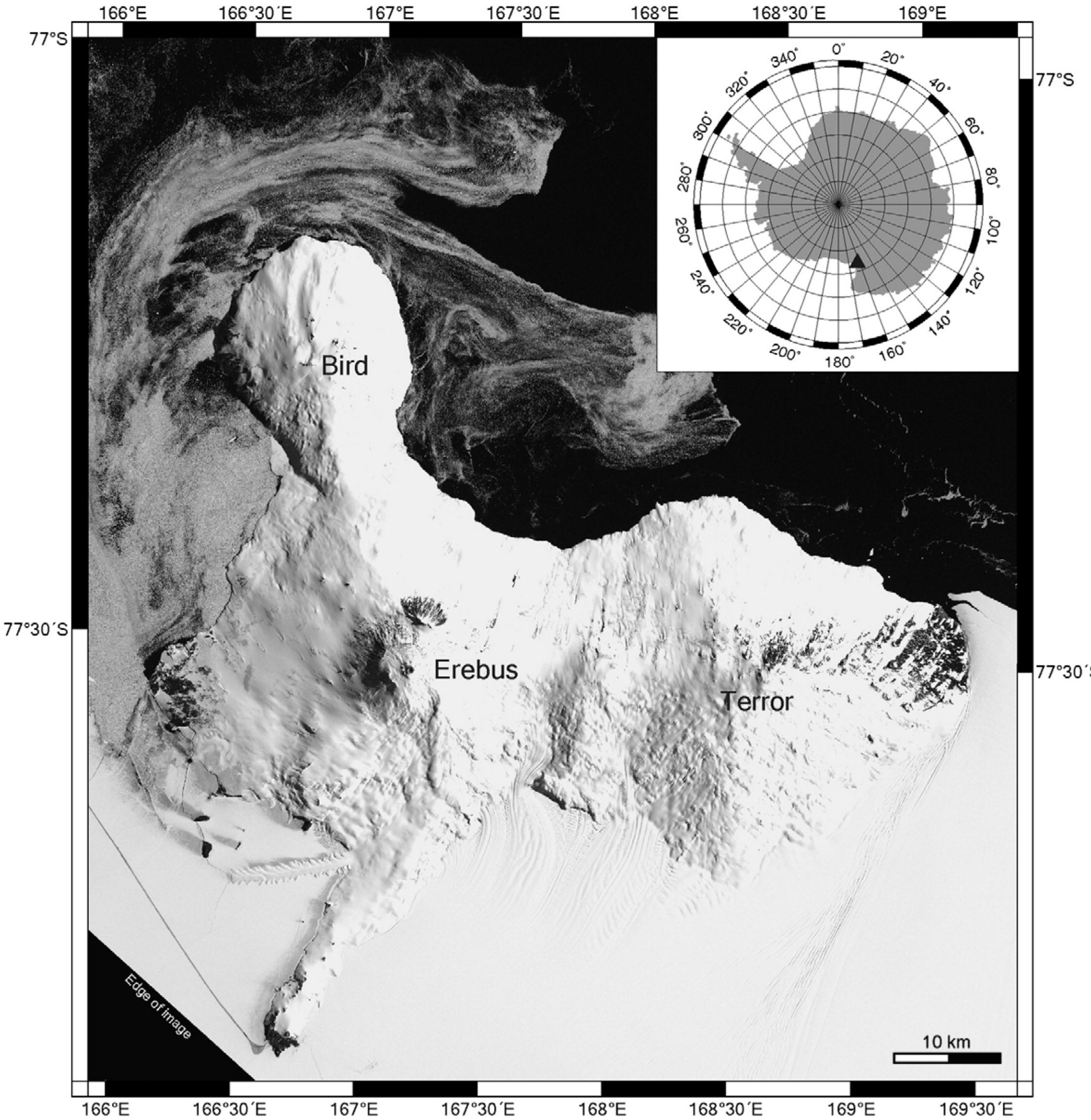


Fig. 1. Landsat 7 Enhanced Thematic Mapper Plus image of Ross Island, Antarctica. The three volcanoes that comprise Ross Island (Erebus, Terror, and Bird) are labeled.

We show how the radiant flux from Erebus' lava lake has varied for the six year period beginning 1 January 2001 and ending 31 December 2006, as recorded by MODIS. Our results indicate that the level of thermal emission from the lava lake, while variable on the time scale of hours, days, and weeks, has remained remarkably stable on an inter-annual basis over at least the last six years. We begin by describing the data and methods used to convert the raw satellite data to an estimate of radiant flux. We then compare the temporal variations exhibited by the Erebus lava lake with those recorded at other terrestrial volcanoes that also host active lava lakes. We end by discussing the role that these observations can play in understanding the behaviour of this open-system volcano.

2. Data and methods

By making measurements of thermal emittance in the shortwave and longwave regions of the electromagnetic spectrum MODIS allows for the detection of active lava at Earth's surface, even though the area covered by such lava is often much smaller than the spatial resolution of the MODIS sensor (1 km at nadir for the emissive bands). Fig. 2 shows a photograph of the lava lake at Erta 'Ale volcano taken on 24 March 2003, while Fig. 2b shows a MODIS image of the area acquired approximately 36 h later (on the evening of 25 March 2003). Even though the lake is only about 35 m in diameter, the spectral radiance it generates by virtue of its high surface temperature makes its location conspicuous in the MODIS image.

MODVOLC (Wright et al., 2002a) is a near-real-time thermal volcano monitoring system that scans the entire MODIS data stream (576 images per day for complete global coverage) and detects the presence of such thermally anomalous pixels. Upon detection, the details of the "hot-spot" pixels (including the time of observation, location, emitted spectral radiance at short and long wavelengths, and the sun-sensor-pixel geometry at the time of observation) are recorded. This algorithm has provided the MODIS spectral radiance data that we have used in this study. Using methods described in detail in Appendix A (see Kaufman et al., 1998, and Wooster et al., 2003 for historical development of our approach) we convert the MODIS measurements of emitted spectral radiance from these pixels into an estimate of the radiant flux from the active lava they contain. In this way, we can estimate the radiant flux from Earth's erupting volcanoes whenever a suitable (i.e. cloud-free) MODIS image is available (see Wright and Flynn, 2004 and Wright and Pilger, in

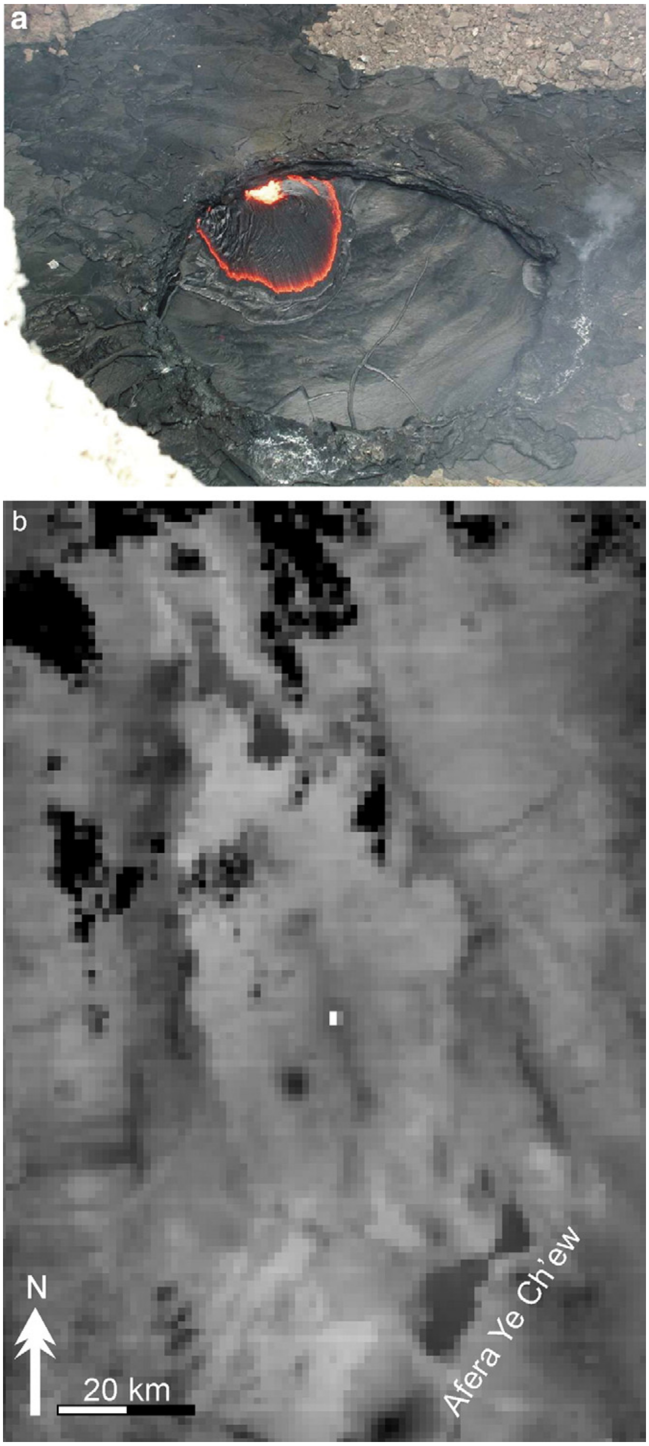


Fig. 2. a) Photograph of the lava lake at Erta 'Ale volcano, Ethiopia, taken on 23 March 2003, by Clive Oppenheimer. Lake is about 35 m in diameter. b) Subset of a MODIS band 22 image (3.959 µm) of the Erta 'Ale range acquired on the evening of 25 March 2003. Each pixel corresponds to an area on the ground of ~1 km. The bright pixels in the center of the image denote high values of emitted spectral radiance caused by the presence of the sub-pixel-sized lava lake.

review). Wooster et al. (2003) estimate that this approach results in radiant flux estimates with an associated uncertainty of about ±30%.

3. Results and discussion

Fig. 3a shows how the radiant flux (Φ_e) from Mount Erebus has varied for the period 1 January 2001 to 31 December 2006. This plot displays results obtained from 4290 individual MODIS images. Only nighttime data are shown, explaining the gaps between late October and mid-February in each year (i.e. during the Austral summer). MODIS bands 22 and 21 cover the same spectral interval (3.929 to 3.989 µm), in which the Earth both emits, and during the day reflects, significant amounts of energy. Spectral radiance data acquired by night are uncontaminated by reflected sunlight and solar heating effects, and are therefore preferable for our purposes (i.e. isolating and estimating the volcanogenic component of a pixel's radiant flux).

First, some cautionary words regarding interpretation of satellite-derived thermal time-series. The MODVOLC data set is not, in any way, screened for the effects of cloud obscuration.

As such, a sharp decrease in the reported radiant flux from one observation time to the next does not necessarily imply that the energy radiated by the lava lake decreased. Complete occultation by a thick cloud deck does not produce this effect because in these circumstances MODIS would record the temperature of the cloud, not the lava lake, and no hot-spot detection event would take place. However, partial cloud cover (or the presence of a layer of cirrus) would serve to depress the at-satellite spectral radiance. A similar result can be expected due to the presence of sub-pixel-sized clouds (or volcanic plume) above the target. An advantage of the MODIS-derived radiance data set that we use here is that the large number of images analysed ameliorates these effects. However, we describe only general trends depicted by the flux time-series we present. To this end Fig. 3b shows the same data, averaged by calendar month.

We estimate that the average radiant flux from Erebus over this six year period was ~15 MW, with a standard deviation of ~8 MW, and a maximum value of ~100 MW. These values are consistent with previous estimates obtained using different methods and data. Radiant fluxes in the range 8–70 MW have been obtained from analysis of high spatial resolution Landsat Thematic Mapper data (Glaze et al., 1989; Harris et al., 1999b) and low spatial resolution Advanced Very High Resolution Radiometer Data (Harris et al., 1997) acquired during the 1980s. Radiant flux of ~40 MW and 17 MW were obtained from the analysis of high resolution data acquired in December 2005 by the Earth Observing-1 Hyperion sensor and Terra ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) sensors (Davies et al., 2008-this issue). Ground based thermal camera images of the Erebus lava lake acquired during 2004 and 2005 field seasons have yielded radiant flux estimates in the range 19–35 MW (Calkins et al., 2008-this issue; Davies et al., 2008-this issue). Variations in radiant flux from a lava lake are a function of the surface area of the lake and the vigour with which convective overturning thermally renews this surface. Oppenheimer et al. (2004) indicate that at time scales of weeks or more, the former is the dominant control, at least at Erta 'Ale.

Fig. 4 compares the radiant flux from Mount Erebus with that observed at Erta 'Ale, Nyiragongo (Democratic republic of Congo) and Ambrym (Vanuatu). All fluxes were computed from the MODVOLC data set using the methods described in this paper. The latter three also currently host active lava lakes, indicative of an open exchange of magma between the lake and sub-surface magma reservoir (although only Erta 'Ale can rival Erebus with respect to longevity). However, the relative stability of the radiant flux from Erebus is striking. At Nyiragongo, radiant flux has gradually increased since the re-establishment of a summit crater lava lake in June 2002 (Wright and Flynn, 2003). The radiant flux from Erta 'Ale exhibits greater variability, consistent with field observations that report large variations in the diameter of the lava lake from as much as ~130 m in February 2001 (Smithsonian Institution, 2001) to ~35 m in March 2003 (Oppenheimer et al., 2004; also see Fig. 2), with two periods (mid to late 2003, and late 2004 to early 2005) when the lava lake had diminished to the point of absence (see Smithsonian Institution, 2004a,b, respectively, for details). The substantially greater flux from the Nyiragongo lake can be explained in terms of its size. Observations made in August 2003 (260 m; Smithsonian Institution, 2003) and

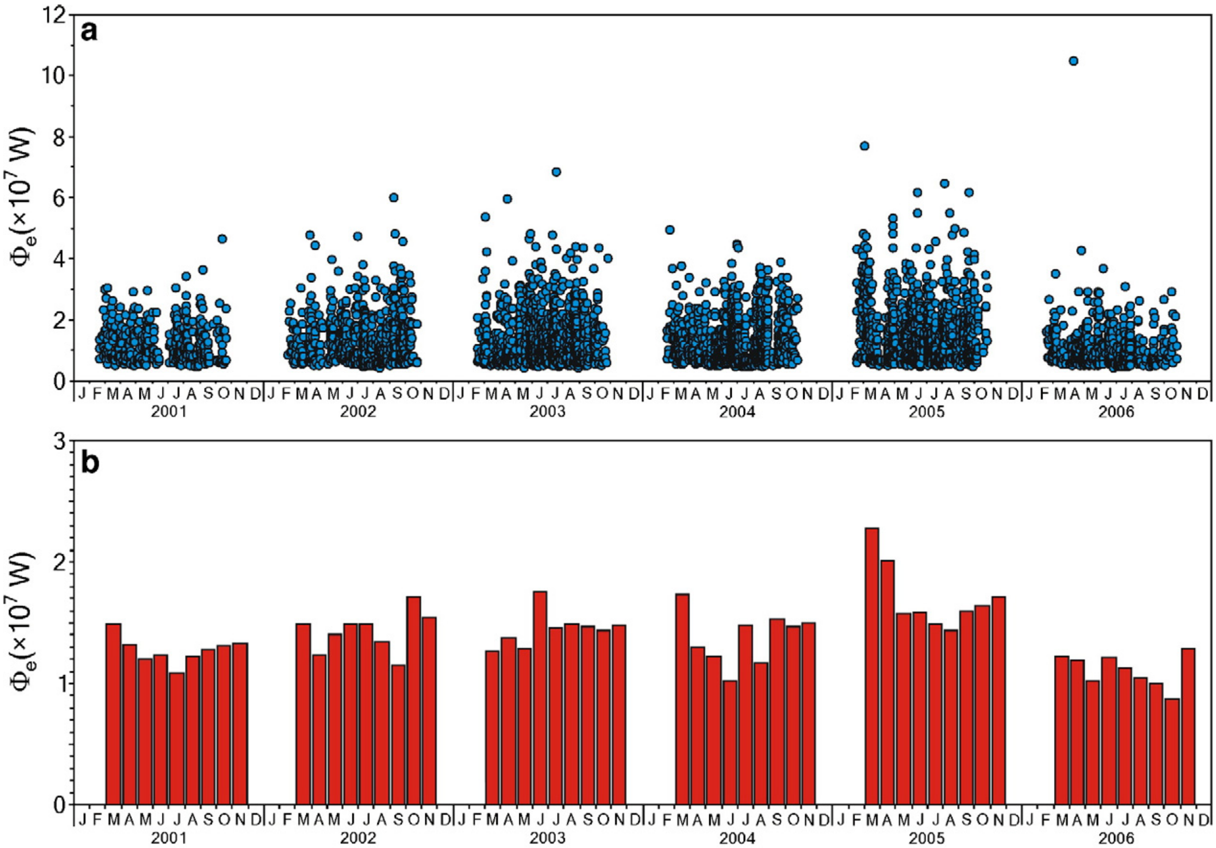


Fig. 3. a) Radiant flux (Φ_e) from Mount Erebus for the period 1 January 2001 to 31 December 2006. Each plot symbol corresponds to a unique MODIS observation. b) The same data, averaged by calendar month.

January 2006 (300 m; Smithsonian Institution, 2006) indicate a diameter for the Nyiragongo lava lake at least two to three time greater than the lake at Erta 'Ale. The satellite-derived radiant flux data are broadly consistent with these observations. Although we do not discuss the Ambrym data, we present them to reinforce the apparent lack of variation in radiant flux from the Erebus lava lake.

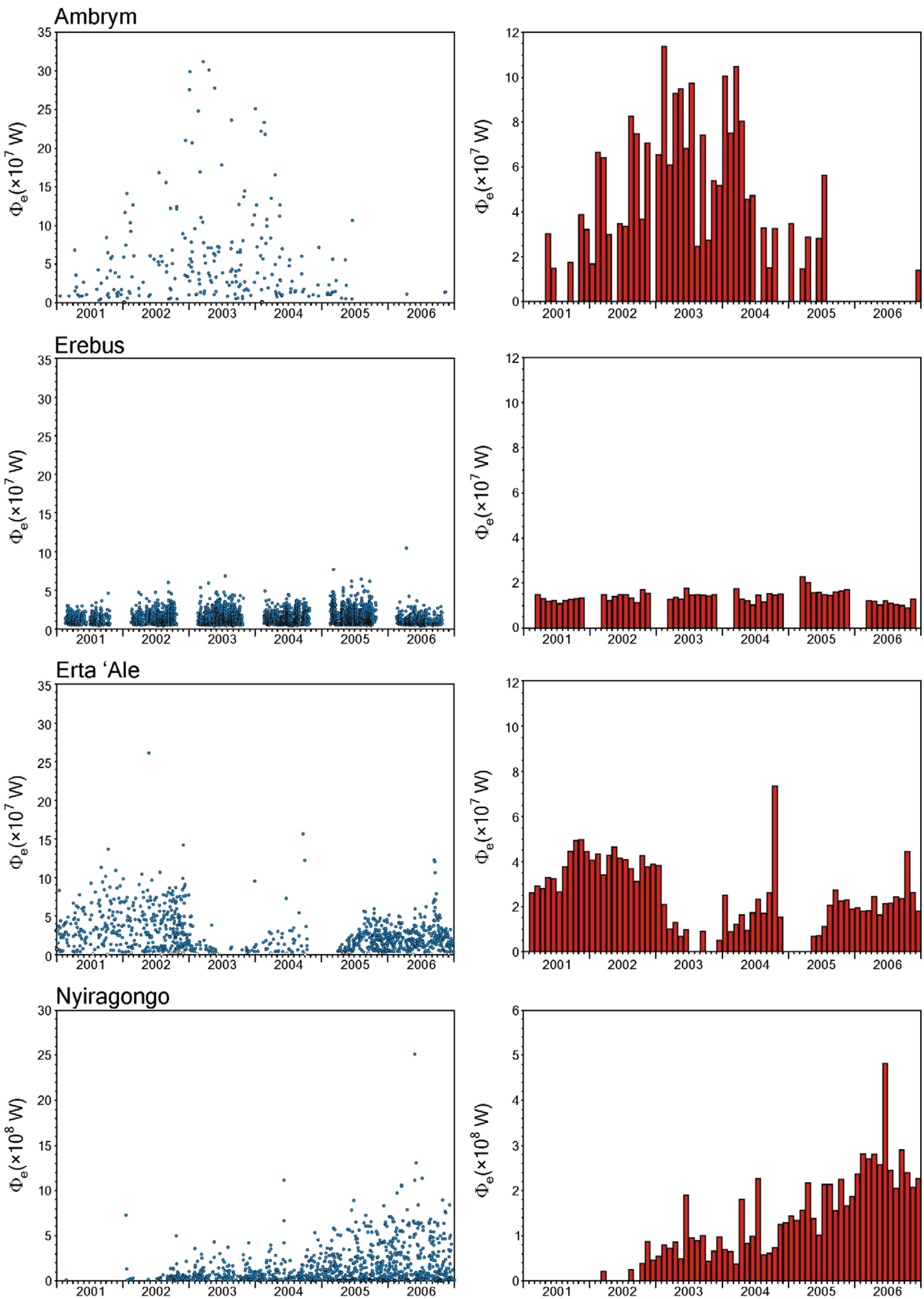
Similar in situ observations are lacking for Erebus during the Antarctic winter. However, the relatively constant radiant flux we report here indicates that the surface area of the active lava (and/or the vigour with which this surface is disrupted and thermally renewed) has not varied significantly over this period. This has significant implications for constraining the nature of magma supply at this volcano. A model often cited to explain the type of activity observed at Erebus (i.e. a persistent flux of gas and heat with little associated extrusion of lava) invokes convection of magma (forced by a combination of cooling, crystallisation, and degassing) along an open conduit linking the vent to a deeper, volatile-rich, magma reservoir (e.g. Francis et al., 1993; Kazahaya et al., 1994; Oppenheimer et al., 2004). As noted by Francis et al. (1993), remote sensing measurements of radiant flux allow for a minimum estimate of the mass of magma required to balance this flux to be made. Following Francis et al. (1993; modified by Harris et al., 1999b) the mass of magma (q; kg) required to yield an amount of energy equal to Q (in J), is given by:

$$q = \frac{Q}{\varphi \Delta f + c \Delta T} \tag{1}$$

where, c is the specific heat capacity of the magma (1.55×10^3 J kg^{-1} K^{-1}), ΔT is the temperature interval over which the magma cools, Δf is the mass fraction of crystals grown over this cooling interval and φ is latent heat of crystallisation (3×10^5 J kg^{-1}). Francis et al. considered two end-member enthalpy models. In the first, the magma is assumed to be emplaced as hyper-abyssal intrusions (having cooled by 50 °C and experienced 25% crystallisation); in the second, the magma is assumed to be emplaced at a greater depth, as cumulates within the magma chamber (having cooled by 400 °C and crystallised fully). Following Wright and Flynn (2004) we assume that the sensible heat flux from the lake surface is at least equal to 30% of the radiant flux. Using Eq. (1), the energy loss from the surface of a lava lake (Q, obtained by integrating Φ_e with respect to time to obtain the energy lost via radiation, then adding an additional 30% of this to approximate energy loss via convection), the minimum mass flux of magma required to balance energy losses from lava lake at Erebus, Erta 'Ale, Ambrym, and Nyiragongo has been calculated. The results are shown in Fig. 5.

Using this model we calculate that a mass flux of at least 14–118 kg s^{-1} is required to balance estimated heat flux from the Erebus lava lake. This represents a six year average. It is, however, not immediately obvious which temporal scale is most appropriate for estimating the magma flux from the reservoir to the surface, using this technique. Lava lakes display a range of behaviours over a range of time scales, including sustained fountaining, discrete strombolian explosions, variations in the rate at which their surface crusts are rifted apart, and variations in lake surface level (Tazieff, 1994). From a remote sensing perspective these factors combine to do two things: increase the surface area of the lake, or vary the average age (and therefore temperature) of that surface, by varying the rate at which the chilled crust rifts apart. Both will cause the radiant flux from the lake surface to vary and hence, upon application of the model embodied in Eq. (1), the apparent magma flux. Ultimately, the energy lost

Fig. 4. Left hand side: Radiant flux (Φ_e) from Ambrym, Erebus, Erta 'Ale, and Nyiragongo, for the period 1 January 2001 to 31 December 2006. Right hand side: the same data averaged by calendar month.


Ambrym
Erebus
Erta 'Ale
Nyiragongo
Φe(×10^7 W)
Φe(×10^8 W)
2001
2002
2003
2004
2005
2006

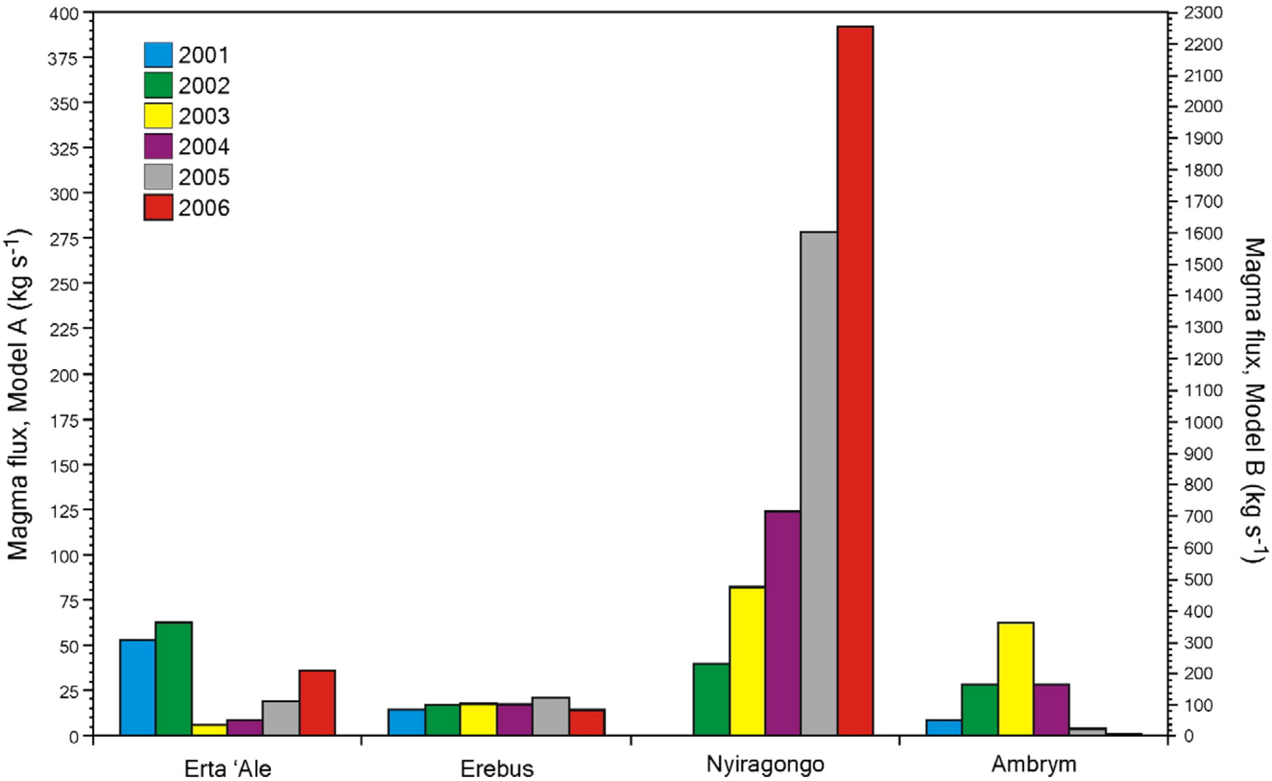


Fig. 5. Mass fluxes (kg s^{-1}) required to sustain estimated energy losses from Erta ‘Ale, Erebus, Nyiragongo, and Ambrym. Model A assumes that this energy is provided by the cooling and crystallisation of magma emplaced as cumulates; Model B assumes the magma is emplaced as dykes.

by a lava lake must in some way be balanced by the energy lost by cooling and crystallising of magma that moves from the reservoir to the surface. However, many things can cause changes in lava lake behavior (and hence radiant flux) which may not be directly indicative of changes in the mass flux of magma from a deeper chamber. In addition to changes in pressure conditions within the magma chamber, the exsolution of volatiles (and the migration and coalescence of bubbles) in the conduit, play a key role (Witham and Llewellin, 2006). The results of analogue experiments presented by Witham et al. (2006) indicate that marked variations in the lava lake depth can result from instabilities generated in the conduit, even when gas flux and reservoir pressure remain constant.

Such changes will manifest themselves as variations in radiant flux from lava lake surfaces, field observations of which indicate substantial changes on timescales of seconds to hundreds of minutes (e.g. Burgi et al., 2002; Oppenheimer et al., 2004; Harris et al., 2005). Given this, the question of what a magma flux estimated from an individual radiant flux measurement actually means becomes relevant. Clearly, any individual radiant flux observation allows for a complementary estimate of mass flux, using Eq. (1). Repeating the calculations described above using just the highest radiant flux observation contained in our MODIS data set (1.1×10^8 W on 10 April 2006) would suggest a mass flux at that time in the range 180–1030 kgs^{-1}, an order of magnitude higher than the six year average. Given the range of behaviors and instabilities predicted for even the simplest of lava lake systems (Witham and Llewellin, 2006; Witham et al., 2006) we propose that long-term averages of heat loss from active lava lakes are more likely to provide useful insights into variations in magma flux from deep reservoirs, than are those obtained from temporally isolated measurements of radiant flux.

Within this context, the radiant flux estimates we present, and the mass flux estimates we derive from them, are significant. Lava lakes are comparatively rare on Earth, and the data presented here provide a unique, long-term perspective regarding the heat and magma budgets for a group of volcanoes that currently host them. The relative stability in the radiant flux observed from Erebus (and by inference the flux of magma required to balance this energy loss) is in marked contrast to that observed at Erta ‘Ale, Nyiragongo, and Ambrym. Although all exhibit characteristics of open-system volcanism, Erebus seems to define the term particularly well. Melt inclusion analyses indicate that degassing of magma at Erebus occurs under open-system conditions (Eschenbacher et al., 2005). Combined with the high and sustained gas fluxes measured at the volcano, the results we present here support to the contention that, with respect to open-system volcanism, Erebus is an archtype.

4. Conclusions

The results we present provide important insights into the behavior of Mount Erebus, as we have already discussed. However, the value of such detailed satellite-derived time-series can be enhanced via correlation with other geophysical datasets (e.g. seismic energy; gas flux), allowing for a both a better understanding of the factors that influence radiant flux and how it can be used as a proxy for other volcanic processes (e.g. Wright et al., 2002b). For example, Kyle et al. (1994) present evidence for a relationship between sulphur dioxide flux and lava lake surface area, the latter being clearly related to radiant flux. Establishment of a similar relationship between SO_2 flux and radiant flux (of the kind we present here) will provide an opportunity to estimate SO_2 flux during the Antarctic winter, when ground-based techniques that rely on solar occultation are unfeasible.

Although we have presented the results obtained from analysis of MODIS data, similar results could be obtained from other polar orbiters such as the Advanced Very High Resolution Radiometer series (see Harris et al., 1997) or the VIIRS (Visible/Infrared Imager/Radiometer Suite; Yu et al., 2005) sensor, scheduled to be launched onboard the first NPOESS platform (National Polar Orbiting Environmental

Satellite System) by 2012. As such, satellite remote sensing can be relied upon to provide an operational capability for monitoring the radiant flux, and behavior, of Mount Erebus.

Acknowledgements

Support is provided by NASA grant NNG04G064G. HIGP publication number 1625 and SOEST publication number 7441. We acknowledge the input of the reviewers.

Appendix A. Estimation of radiant flux from MODIS data

Wooster et al. (2003; Eq. (6b) therein) show how the energy radiated from the MODIS hot-spot pixel (Φ_e; J s^{-1}) can be obtained by using:

$$\Phi_e = 1.89 \times 10^7 (L_{MIR} - L_{MIR,bg}), \tag{A1}$$

where L_{MIR} is the spectral radiance from the hot-spot pixel (i.e. pixels that contain active lava) recorded at 3.959 μm, and L_{MIR}, bg is the spectral radiance from pixels that do not contain active lava (in units of W m^{-2} sr^{-1} μm^{-1}). Although Wooster et al. (2003) derived this method for estimating energy fluxes from wildfires, it is equally amenable to the analysis of active lavas. For each MODIS nighttime observation we calculate Φ_e, for each hot-spot pixel detected by the MODVOLC algorithm. We use only nighttime data because at night L_{MIR} is uncontaminated by spectral radiance attributable to solar heating and reflected sunlight. The total flux from the cluster as a whole is then determined by summation, providing an estimate of the radiant flux by the entire lava lake surface at the moment of satellite overpass. Eq. (A1) allows radiant flux to be estimated to ±30% when the effective temperature (i.e. the single temperature that results from solving Eq. (1) for various combinations of T and f) of the MODIS pixel lies in the range 600–1500 K (Wooster et al., 2003).

The MODVOLC data stream contains data only for those pixels that exhibit anomalous levels of thermal radiance. As such, it provides L_{MIR} for each hot-spot pixel, but does not provide $L_{MIR,bg}$. In the work of Wooster et al. (2003) it is assumed that this value is determined by taking, for example, the average $L_{3.959}$ of the halo of pixels immediately surrounding the hot-spot cluster. MODVOLC does not record the radiances of these pixels. However, this background value can be approximated from the radiance values contained within the MODVOLC dataset. The relationship between spectral radiance and temperature varies as a function of wavelength: at 3.959 μm (MODIS bands 21 and 22) $L_\lambda \sim T^4$, whereas at 12.02 μm (MODIS band 32) the relationship is approximately T^2 (note this is the approximate linearity of the Planck blackbody flux from an isothermal surface over the temperature range ~300 to 1000 °C; Wooster and Rothery, 1997). As a result, MODIS band 32 is much less responsive to the presence of active lava within the image pixel (Fig. 2b). Thus, the band 32 hot-spot radiance dataset can be used to obtain a proxy for $L_{MIR,bg}$ if the sub-pixel-sized hot-spot is small. Clearly, as the size of the lava body increases, this assumption becomes invalid. To find the band 32 radiance that most closely approximates a non-lava contaminated "background" value, we analysed all hot-spot pixels recorded at the volcanoes we refer to in this paper for the period 1 January 2001 to 31 December 2006. For each volcano we grouped the band 32 radiances by calendar month and selected the lowest value (after excluding, as outliers, those values more than one standard deviation below the mean). In this way, we use the band 32 hot-spot data to approximate $L_{MIR,bg}$. in a way that a) eliminates anomalously low (cloud-contaminated) values and b) compensates for seasonal variations in background temperature. L_{MIR} was obtained primarily by using band 22, which has a higher radiometric precision than band 21 (0.07 K and 2.0 K, respectively). However, when the emitted radiance exceeded the upper measurement limit of the band 22 detectors, band 21 data were used. Band 21 has a much larger measurement range (up to ~450 K; cf. ~340 K for band 22).

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